Aalborg Universitet

Junction Temperature Control for More Reliable Power Electronics

Andresen, Markus; Ma, Ke; Buticchi, Giampaolo; Falck, Johannes; Blaabjerg, Frede; Liserre, Marco

Published in:
I E E E Transactions on Power Electronics

DOI (link to publication from Publisher):
10.1109/TPEL.2017.2665697

Publication date:
2018

Document Version
Publisher's PDF, also known as Version of record

Link to publication from Aalborg University

Citation for published version (APA):
Andresen, M., Ma, K., Buticchi, G., Falck, J., Blaabjerg, F., & Liserre, M. (2018). Junction Temperature Control for More Reliable Power Electronics. *I E E E Transactions on Power Electronics*, *33*(1), 765-776. [7892031]. https://doi.org/10.1109/TPEL.2017.2665697

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal -

Take down policy
If you believe that this document breaches copyright please contact us at vbn@aub.aau.dk providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from vbn.aau.dk on: May 06, 2023

Junction Temperature Control for More Reliable Power Electronics

Markus Andresen, *Student Member, IEEE*, Ke Ma, *Member, IEEE*, Giampaolo Buticchi, *Senior Member, IEEE*, Johannes Falck, *Student Member, IEEE*, Frede Blaabjerg, *Fellow, IEEE*, and Marco Liserre, *Fellow, IEEE*

***Abstract*—The thermal stress of power electronic components is one of the most important causes of their failure. Proper thermal management plays an important role for more reliable and cost-effective energy conversion. As one of the most vulnerable and expensive components, power semiconductor components are the focus of this paper. Possible approaches to control the semiconductor junction temperature are discussed in this paper, along with the implementation in several emerging applications. The modification of the control variables at different levels (modulation, control, and system) to alter the loss generation or distribution is analyzed. Some of the control solutions presented in the literature, which showed experimentally that the thermal stress can be effectively reduced, are reviewed in detail. These results are often mission-profile dependent and the controller needs to be tuned to reach the desired cost-benefit tradeoff. This paper analyzes also the many open questions of this research area. Among them, it is worth highlighting that a verification of the actual lifetime extension is still missing.**

***Index Terms*—Thermal management of Electronics, Temperature control, pulse width modulation inverters.**

I. Introduction

POWER semiconductor modules are built of different layers of copper and substrate to ensure electrical insulation on one hand and a good thermal conductivity on the other hand [1]. For the electric connection between chips and terminals, aluminum bond wires are typically used [2], although copper has seen an increasing interest [3]. The scheme of a power electronics module with the different materials stacked on a direct-bond-copper (DBC) substrate is shown in Fig. 1.

Variations of the ambient temperature and power variations create cyclic heating and cooling processes, also called thermal cycles. Due to different thermal expansion coefficients (CTE) of copper and the ceramic of the substrate, mechanical stress between the material layers occurs when the temperature changes [4]. Although all interfaces experience stress due to different CTE, it has been observed that a large difference affects the aluminum and the silicon chip and the solder between ceramic substrate and base plate [5]. For frequent repetition of thermal cycles, the resulting expansions and contractions of the material lead to fatigue of solder joints [1], and thus, cause aging [6]. Therefore, thermal cycles are an important cause of failures and destruction of the power modules [7]. The thermal cycle magnitude is the most critical parameter for the scale of the aging [8]. In [9], the advancing degradation of a base plate solder in a power module has been observed for increasing amount of applied thermal cycles using acoustic microscopy. After 4000 cycles with a magnitude of 80 K, about a quarter of the solder has been cracked, leading to dramatic increment of thermal resistances within the module. The consequences are increased temperatures in the chips, and thereby, increased losses. This forms a positive feedback loop, which accelerates the aging process [10]. Especially short-term thermal cycling in the order of a second that is mostly evoked by power cycling leads to fatigue of the bonds, and therefore, may cause bond wire lift off [11]. Many manufacturers of power electronic devices, such as power semiconductors or capacitors, have developed their reliability models, which normally are based on accelerated or aging tests, and are able to evaluate the lifetime information according to certain thermal behaviors of the components. Therefore, the thermal stress of the power devices needs to be assessed and properly controlled. In the energy conversion system, the power or current flowing through the converter is normally designed according to the available electrical or mechanical power level. As a result, if the available power processed by the converter system is not constant, as in the renewable energy or motor

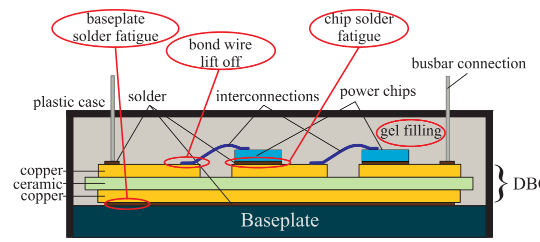


Fig. 1. Structure of a power electronic module.

Manuscript received August 6, 2016; revised November 15, 2016 and January 11, 2017; accepted February 3, 2017. Date of publication April 4, 2017; date of current version October 6, 2017. This work was supported by the European Research Council under the European Union's Seventh Framework Programme (FP/2007-2013)/ERC Grant Agreement 616344—HEART. Recommended for publication by Associate Editor A. Lindemann. *(Coresponding author: Giampaolo Buticchi.)*

M. Andresen, G. Buticchi, J. Falck, and M. Liserre are with the Chair of Power Electronics, Christian-Albrechts University of Kiel, 24118 Kiel, Germany (e-mail: ma@tf.uni-kiel.de; gibu@tf.uni-kiel.de; jofa@tf.uni-kiel.de; ml@tf.uni-kiel.de).

K. Ma is with the Department of Department of Electrical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China (e-mail: kema@sjtu.edu.cn).

F. Blaabjerg is with the Department of Energy Technology, Aalborg University, 9220 Aalborg, Denmark (e-mail: fbl@et.aau.dk).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TPEL.2017.2665697

0885-8993 © 2017 IEEE. Translations and content mining are permitted for academic research only. Personal use is also permitted, but republication/redistribution requires IEEE permission. See http://www.ieee.org/publications_standards/publications/rights/index.html for more information.

drive applications, the complicated and variable mission profiles will be directly reflected by the loading variation in the power electronics components, which results in complicated thermal cycling that can quickly trigger the wear-out of the components.

Another problem is that the temperature of the device is normally hard to access and it is difficult to monitor it during operation as well as it is difficult to validate thermal models; this calls for estimators/observer in order overcome the direct measurement problem. One effective way to extend the lifetime and improve the reliability of components is to push the overall stress range of the components to a lower level.

In the case of a converter system, active thermal control (ATC) reduces the thermal cycling of the components either by reducing the fluctuation amplitude or by reducing the mean level of the temperature, while the design of the converter does not need to be changed, meaning that there is no additional cost for the enhancement of the converter design or components [12]–[14]. These topics have not yet been comprehensively summarized and this paper serves to give a review on these topics.

Section II describes the lifetime estimation of power modules and the most common causes of failure, Section III discusses the basics of temperature estimation and control, Section IV details the possibilities of ATCs, Section IV presents its applications, and Section V draws the conclusions.

II. Lifetime of Power Electronic Modules

Failures in power modules impact safety in operation and cause downtimes, giving extra cost for the operators of the system.

For manufacturers and operators of power electronic modules, it is of interest to estimate the impact of certain usage on the lifetime of the modules [15]. The lifetime of a system is an important parameter, as cost calculations for purchase, maintenance, and replacement depend on it. The aim of a lifetime prediction is to assess how long a module can be used without expecting to see a failure for a particular application. In the 1950s, the first relationship between the plastic strain amplitude and the number of cycles to failure were established by Coffin and Manson in studies on fatigue in material science caused by cyclic plastic deformations [16]. Since all materials expand and shrink due to thermal cycles, nowadays modified relationships are also used to estimate the capability of power semiconductors to withstand thermal cycles. The parts more susceptible to thermal cycling are highlighted with red color in Fig. 1. Based on this, a well-known approach to estimate the module's lifetime is the Coffin–Manson–Arrhenius model [17]: The number of cycles to failure N_f is described in dependence of the amplitude of thermal cycles ΔT_j and the average temperature T_{jm}. Other coefficients a, α, and E_a are extracted from a dataset of multiple reliability experiments and they are adjusted for best match to the module [18] and k_B is the Boltzmann constant. Its analytical equation is

$$N_f = a \cdot \Delta T^{-\alpha} \cdot e^{\frac{E_a}{k_B T_{j,m}}}. \tag{1}$$

Other researchers have modified this relationship, recognizing for instance the frequency of thermal cycles, heating and cooling times as well as more electrical parameters in the Bayerer model [19]. Manufacturers of semiconductors use this relationship to determine the thermal cycle capability of their modules. Fig. 2 shows this for a Semikron module with coefficients matched to IGBT4 modules [18]. To rate the impact of a certain mission profile on the module's lifetime, first a temperature profile is created from the power profile, calculating the losses in the semiconductors, thermal-related characteristics and environmental influences. This thermal profile contains normally thermal cycles of different magnitudes at different average temperatures, so a direct derivation of the accumulated damage with (1) is not possible. In order to combine the damage caused by these different thermal cycles, Miner's cumulative damage rule can be adopted [4]. Miner's rule is written as

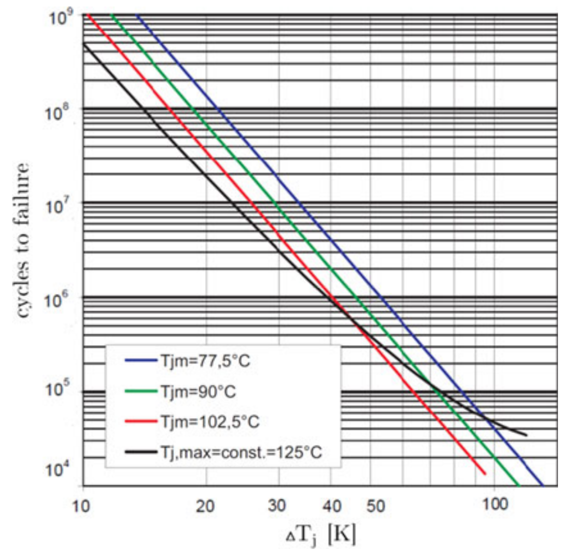


Fig. 2. Temperature cycle capability characteristic N_f for standard SEMIKRON IGBT modules [18].

$$C = \sum_i \frac{n_i}{N_i}. \tag{2}$$

Here, C is the cumulative damage, n_i the number of cycles in the stress range i, and N_i the number of cycles to failure in the ith stress range. Thus, the more thermal cycles occur in the mission profiles the more the cumulative damage will rise. If the cumulative damage reaches 1, the module will fail according to the model [20].

Instead of using a model-based approach, another possibility to detect the aging of a module during operation is the measurement of a physical parameter such as the collector–emitter voltage v_{ce}. An increment of v_{ce} is observed for bond wire liftoff [21]. However, v_{ce} is also sensitive to the applied power level and changes in the temperature. It is worth noting that the measurement of v_{ce} shows marked variation when the device is approaching the end-of-life, while it is fairly constant during the normal conditions. Due to this fact, although v_{ce} measurement could be used to get a lifetime indication, it is more suitable to detect an incipient fault than to estimate the residual lifetime. By knowing the influencing factors and indicators for the lifetime of the power semiconductors, it is possible to control some of the influencing variables during converter operation to influence the lifetime of the power semiconductors. This is referred to as ATC and will be discussed in the next section.

III. Semiconductor Junction Temperature Estimation and Control

ATC is a new concept recently introduced to regulate power losses and control the thermal stress. The general principle is to vary temperature-related control variables of the system to influence its junction temperature in order to reduce damage caused by thermal cycling [22]. Since the junction temperature is difficult to measure, an important part of the ATC algorithms is the temperature estimation. These parts will be detailed in the next paragraphs.

A. Temperature Estimation

An accurate real-time estimation of the junction temperatures of a power module is of interest for ATC. Measurements of the junction temperatures are possible as well, but the sensors need to have a bandwidth in the order of a magnitude higher than the expected thermal cycles. Usually thermocouples connected to the chips cannot reach the necessary bandwidth demand for their detection. A high-bandwidth temperature measurement equipment is expensive and only used in specialized or experimental setups. For commercial product solutions, junction temperature estimations on the basis of electrical measurements are more realistic as there is no need to increase complexity of power modules [23]. Electrothermal models for this purpose consist of three parts: A device model that holds the dynamic characteristics of the used power module, a power losses model for the semiconductors, and a thermal model to estimate the heat propagation in the module [22]. Another way to estimate the junction temperature is the use of thermo-sensitive electrical parameters (TSEP) in the module. Classical TSEPs are the collector–emitter voltage drop at low current, the threshold voltage, and saturation current of metal–oxide–semiconductor gated devices [23] and the short-circuit current [24]. However, measurements of TSEPs require additional circuitry.

B. Temperature Control

A simple approach to achieve temperature control is to adjust the switching frequency as it has a direct influence on the power losses without notably affecting the operating point of the application when adjusted within system constraints. The switching frequency control is done using linear control [13] or hysteresis control [14], [25]. A dynamic limit of the inverter current under thermal constraints is proposed in [13]. This enables low-power operation of nearly overheated systems to prevent further rise in temperature, and thereby, a complete shutdown or damage of the module due to over temperature. Another approach is to manipulate the loss distribution between IGBTs and diodes, by adjustment of the dc-link voltage, which influences the modulation index [26]. This can be used to relieve specific semiconductors on the cost of additional losses in the inverter caused by a higher current magnitude. In modular multilevel converters (MMC), the modules are stressed unequally in specific conditions, leading to higher thermal stress in particular modules. An algorithm is proposed in [27] and [28] and for active balancing the junction temperatures of the MMC cells. In [29], power routing is used to balance uneven loading of cells in the smart transformer (ST). In [13] and [14], the used active thermal controllers decrease the switching frequency below that of the uncontrolled system at the price of an increase in the current ripple. In a comparison in [25], the active thermal controller is reducing the current and is, therefore, influencing the mission profile.

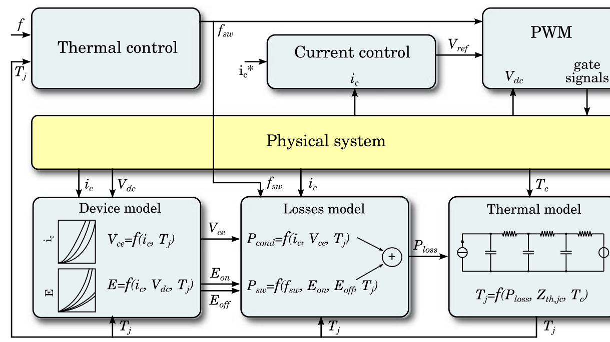


Fig. 3. Example of a model-based active temperature control scheme.

Since the thermal behavior is changed via the control, there are as many possibilities as control layers and variables. The lowest level is the gate driver that can be used directly to influence the losses of the power devices. Also modified modulation patterns can be employed to this aim. The converter's control level generates the reference signals for the modulator and in this case active derating can be performed, or modification to some control variables (dc-link, switching frequency) can be realized without altering the normal converter's operation. At the highest level, there is system control, where the presence of multiple power converters can be exploited to alter the losses distribution or to create additional losses without affecting the main converter's goal. In the following sections, the possibilities for each control level will be explored and an analysis on how these techniques can be applied to specific applications will be carried on.

Considering the previously reviewed ATC approaches, a control scheme using the switching frequency to influence the junction temperature, as it is the most common temperature control parameter, is depicted in Fig. 3. In the scheme, the load current i_c, the dc-link voltage V_{dc} and a small bandwidth measurement of the modules case temperature T_c are sensored in the physical system. In addition, the semiconductor's characteristic curves are taken to determine the collector to emitter voltage drop V_{ce} and the switching energies E_{on} and E_{off}. They are used to achieve an estimation of the conduction losses P_{cond} and the switching losses P_{sw}, which are given to the thermal network to calculate the resulting junction temperature. The thermal controller sets the switching frequency independent from the current reference i_c^*, but to achieve the selected target, that could be temperature limitation (then the maximum allowable junction temperature can be used as reference) or thermal cycle reduction. To filter the junction temperature's fluctuation of the fundamental frequency, f is used as an input.

Another strategy to perform ATC relies on the active control of the cooling system. In [30], the authors control the speed of the fan in order to reduce the power cycling of the estimated junction temperature. Although this technique can be adopted in all system that feature a controllable cooling, the focus of this paper is on the solutions that modify the electrical parameters of the control

IV. Implementation Possibilities for ATC

A. Thermally Conditioned Gate Driver

Active gate control is a possibility to control the semiconductor losses, without affecting the functionality of the device. As the gate drive voltage influences both conduction and switching losses of the semiconductors, it can be used to decrease the thermal cycling [32]. In the literature, an active gate driver has been reported that is applied for counteracting variations in the on-state resistance of the IGBTs [33]. Another active gate control has been used to balance the currents among parallel-connected IGBT devices [34]. By adjusting the control parameters in these active gate controls, they can also be applied to reduce the thermal cycling in the semiconductors. Active gate control in the context of GaN power semiconductors is of particular interest. Compared to Si-devices, GaN-devices provide a much higher switching speed and possibly higher operating temperature. As a consequence, they have an increased power density, which makes the temperature management critical, especially for the PCB and components to which the GaN is connected. Therefore, active gate control has been applied in [31] to reduce the thermal cycling in a GaN-based dc/dc converter. In Fig. 4(a), the variation of energy loss during turn OFF of the device is shown dependent on the tunable parameter ($T_{\rm on}$) of the active gate driver, that represents the time during which the gate is fed with an intermediate voltage level. Having a three-level gate driver with controllable on-time allows controlling the slew rate and the conduction losses of the device. In Fig. 4(b), the impact of a variation of the switching losses of a GaN device on its junction temperature is shown. This simulation shows the possibility of reducing the thermal cycling by varying the device losses using the gate driver.

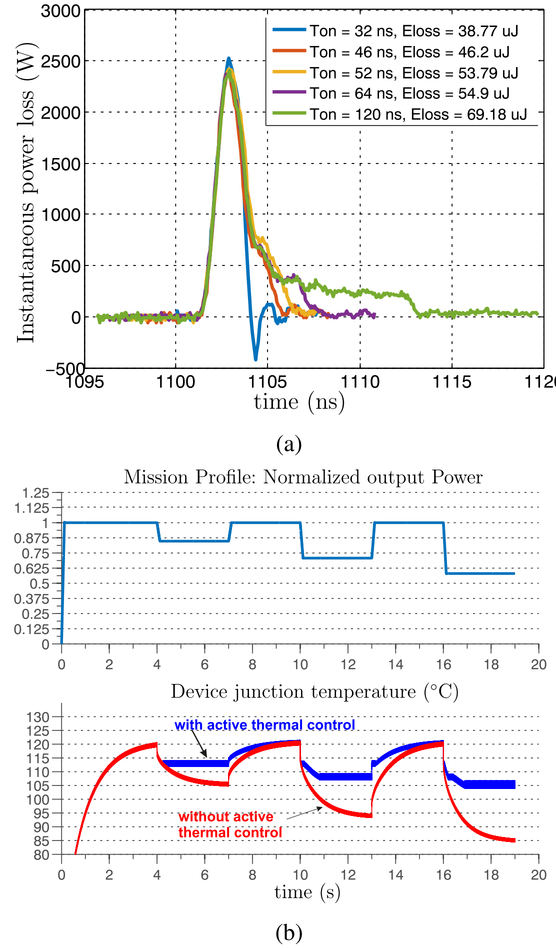


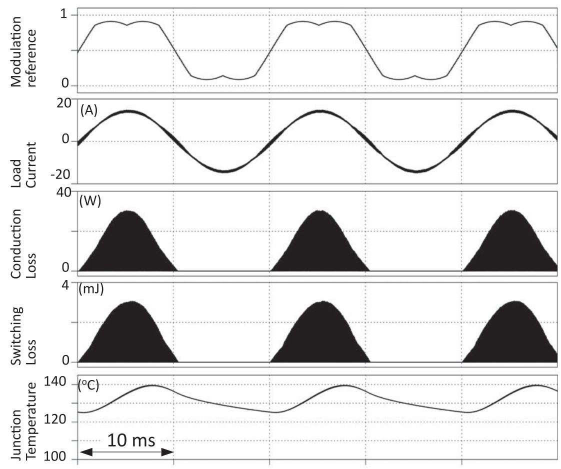
Fig. 4. Two-step gate driver applied to a GaN enhancement-mode high-electron-mobility transistor. (a) Energy loss variation depending on the duration of the intermediate gate voltage step. (b) Simulation of ATC of the junction temperature variation of the switching loss energies for 400 V and a switching frequency of 100 kHz [31].

B. Thermally Modified Modulation

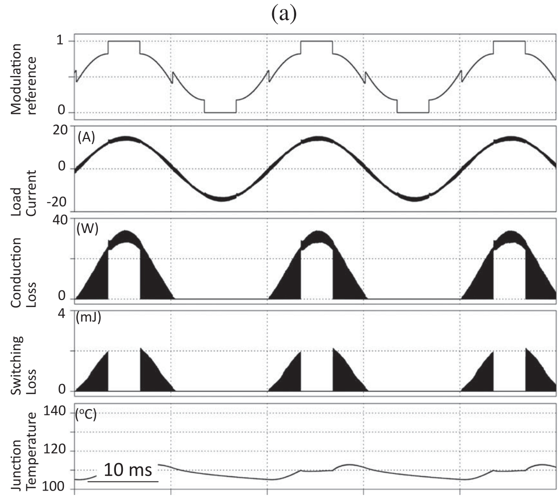
Another way is to explore the modulation methods. The discontinuous pulsewidth modulation (DPWM) in two-level three-phase converter is a well-known strategy for the device loading control, as it is shown in Fig. 5. The principle of DPWM is to clamp the voltage reference of the converter output to the upper or lower dc-link potential in a certain interval so that the corresponding power device will keep its status without switching, and the switching loss is, thereby, mitigated in that interval. Since the total loss of the power device during this clamping period is reduced, the mean value and variation of the junction temperature are therefore both reduced. The thermal control by using DPWM can also be a benefit in the thermal optimization of multilevel converters. A case study on a three-level neutral-point-clamped (3L-NPC) converter can be found in [35], where several different modulation methods in terms of optimal zero sequence injection (Opt-ZSSPWM) [36], conventional 60° DPWM (CONV-60° DPWM) [37], and alternative 60° DPWM (ALT-60° DPWM) [37] are applied to the converter. It has been reported in [36] that with CONV-60° DPWM and ALT-60° DPWM, the junction temperature of the device with the highest temperature (Cl. Diode1) can be reduced significantly.

Besides the switching losses, the PWM strategies can also alter the conduction losses of power devices, and thereby, achieve the thermal control target. The space vector diagram (SVD) for a 3L-NPC converter is shown in Fig. 6. It is composed of 27 switching states/state vectors, which can be grouped into 3 zero vectors, 12 short vectors, 6 medium vectors, and 6 long vectors according to the length in the diagram. The numbering "2," "1," and "0" of the state vectors represent that a certain phase is connected by the converter to the positive dc bus, the neutral point and the negative dc bus, respectively.

By looking at the SVD of the 3L-NPC converter, as shown in Fig. 6, which is used for the space vector modulation (SVM) of

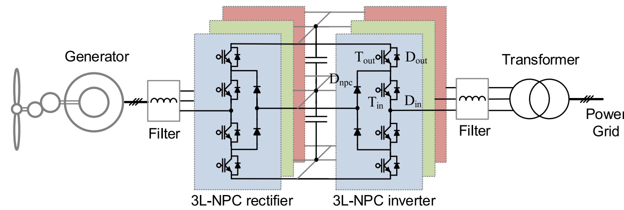


(a)

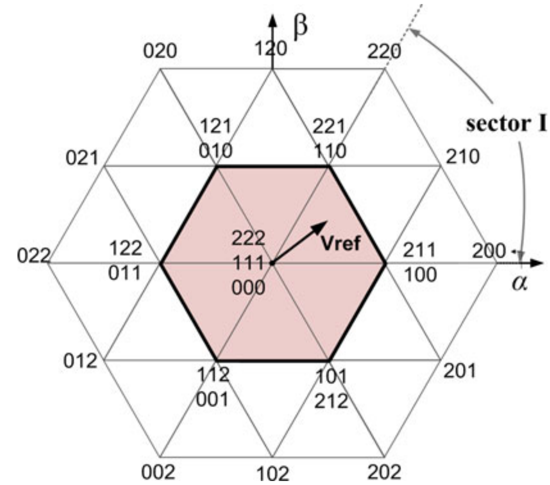


(b)

Fig. 5. Power loss and junction temperature of the IGBT in a B6 converter with different modulation schemes: (a) space vector pulsewidth modulation; (b) DPWM (switching loss:conduction loss = 3.56:1).



(a)



(b)

Fig. 6. 3L-NPC converter. (a) Back-to-back topology and configuration for a wind turbine application. (b) SVD.

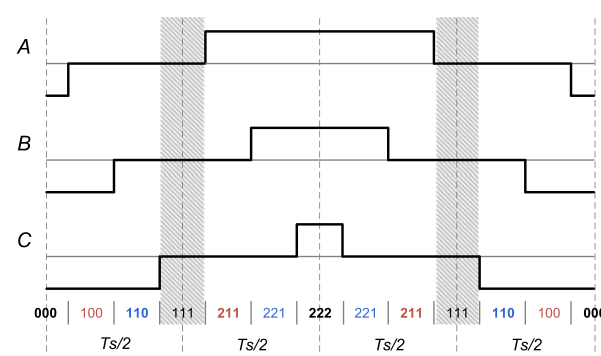


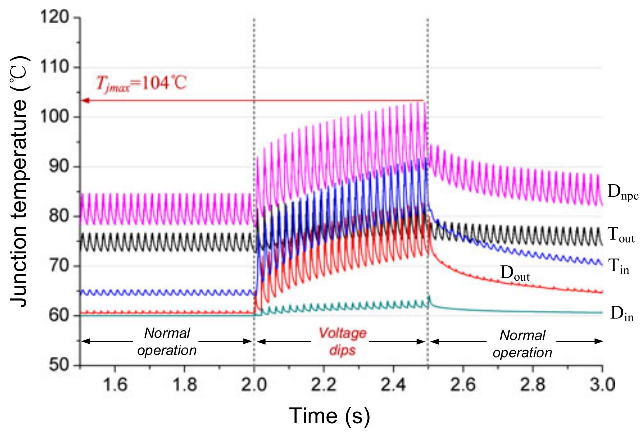
Fig. 7. Optimal modulation sequence for relieved device temperature under low-voltage ride through (LVRT).

the three-phase converter, it can be seen that all state vectors at the inner hex of the SVD have switching redundancies. These switching redundancies provide the control flexibility to modify the current paths flowing in the power devices, and thereby, modifying the conduction losses of the device. This feature is especially interesting for the ride-through operation during the grid faults for grid-tied converters [38], or the start-up operation of motor drives, where the voltage reference vector is normally low in amplitude and it is located in the inner hexagon in Fig. 6 [38], [39].

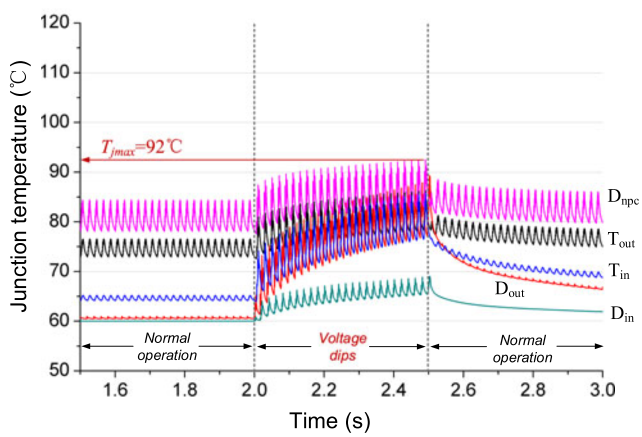
Based on this concept, a series of optimized modulation sequences have been proposed in [38], and one of the SVM sequences within one switching cycle is shown in Fig. 7. It can be seen that the state vector 111, which connects the three-phase output of the converter to the neutral point of the dc bus, is eliminated, indicating that the time of the converter state when the current is flowing through the clamped diode and inner switch of 3L-NPC will be reduced. The simulation results of the device temperature in the 3L-NPC converter under a low-voltage output is shown in Fig. 8. It can be seen that when applying the optimized modulation sequence, the thermal loading among the devices is more symmetrical, and the thermal loading of the most stressful devices are also reduced.

C. Thermally Oriented Control of the Power Converter

The converter controller generates the reference for the lower level systems that implement the modulation, meaning that at this level the ATC can be used to modify the control variables. The goal can either be the junction temperature limitation, in order to perform an active derating that pushes the semiconductors close to their limits with a minimum overdesign or the thermal cycle reduction, as depicted in Fig. 9. An additional block is used to observe the junction temperature, T_j. The junction



(a)



(b)

Fig. 8. Device temperature reduction of 3L-NPC under LVRT of 500 ms [38]: (a) with normal modulation; (b) with optimal modulation.

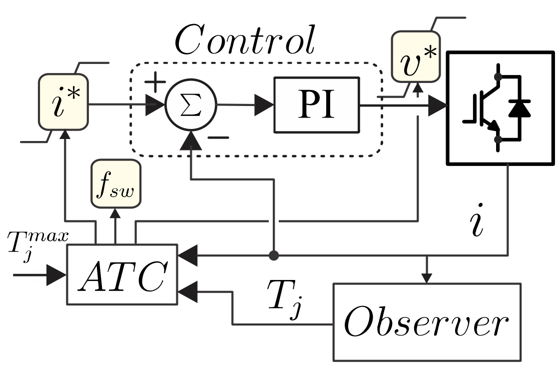
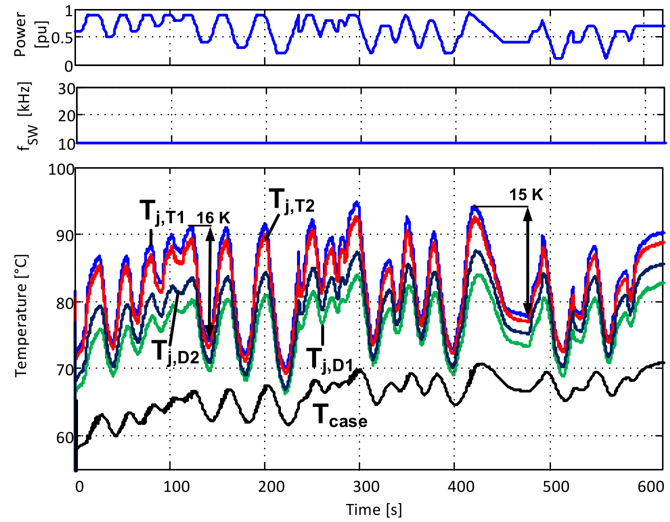


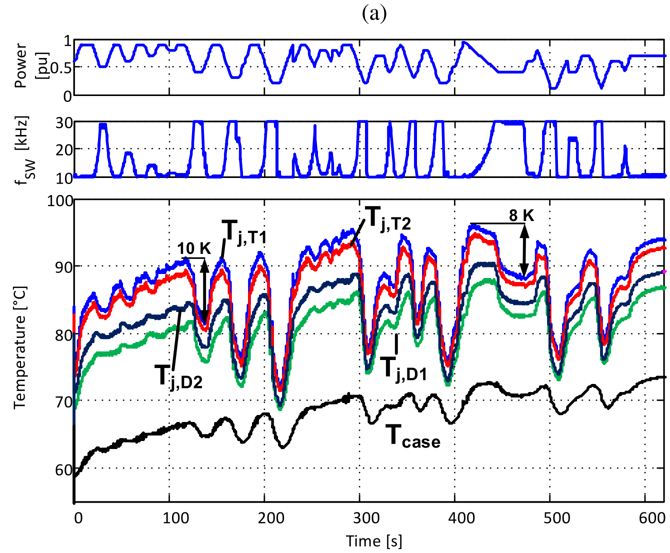
Fig. 9. Basic scheme for ATC at the converter's control level.

temperature limitation normally involves the saturation of a control variable (voltage, duty cycle, current) when the temperature reaches a certain level.

Thermal cycle reduction without affecting the system operation can be achieved when the degrees of freedom of the control are used, and they are also application dependent. In particular, in [22] and in [40], for a single-phase H-bridge IGBT converter, thermal cycle reduction was achieved by modifying the switching frequency of the converter to eliminate the fast thermal cycles. This is achieved by increasing the losses, when



(a)



(b)

Fig. 10. Experimental results of the ATC using switching frequency variation between 10 and 30 kHz [40].

the output power drops to prevent the system to cool down. To validate the functionality of the proposed method, a mission profile with highly fluctuating power is used and the junction temperature is measured for a fixed switching frequency and afterwards by its adaption for ATC. As it can be seen from the measurement in Fig. 10, the active thermal controller allows to strongly reduce the temperature variations during a fast changing power demand. For achieving the compensation of thermal cycles, the thermal controller needs to be tuned in an appropriate way. Otherwise, the risk is to only increase the losses without reducing the thermal cycling. This problem is addressed in [41]. The drawback of this solution is that the increased losses cause an average increase of the mean junction temperature. Depending on the main cause of failure, i.e., thermal cycling or average temperature, the damage due to the slightly higher average mean temperature cannot become relevant.

The limit of modulator based ATC structures is that they cannot reduce the thermal stress in a specific semiconductor, as the

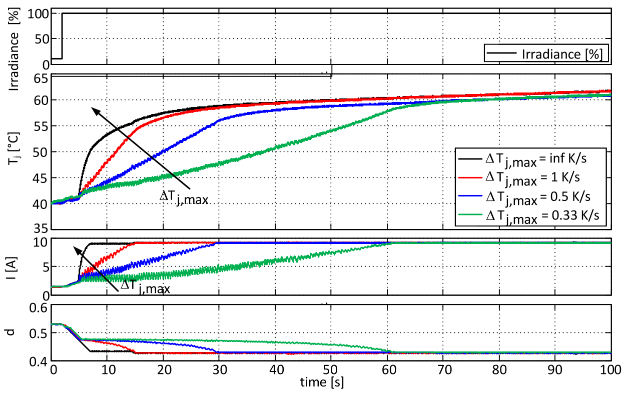


Fig. 11. Behavior of the MPPT for a step in the irradiance from $P_{\mathrm{PV,rel}} = 10\%$ to $P_{\mathrm{PV,rel}} = 100\%$ for different temperature gradients and normalized starting temperature in one IGBT. Irradiance, junction temperature, input current, and duty cycle of the boost converter are shown.

conductivity and switching of the semiconductors in the converter is selected by the modulator. In [42], a thermal controller is presented, that applies a finite control-set model predictive control in order to achieve a more precise junction temperature control. The predictive control selects the optimal switching vector, that fulfills the applications demand and reduces the thermal stress. This switching vector is directly applied to the physical system. The possibility to modify the control variable to limit the maximum junction temperature was first proposed in [13]. Another possibility is to reduce the maximum temperature derivative, which at the same time reduces the thermal cycle. This concept was explored in [41], where the duty cycle of a dc/dc converter for the photovoltaic system was actively modified in order to limit the maximum junction temperature derivative in the presence of irradiation changes. This algorithm modifies the maximum power point tracking (MPPT) embedded in this kind of converters. In Fig. 11, the functionality of the derivative limitation is shown for this thermal-optimized MPPT and it is possible to see that the IGBT temperature can be effectively controlled by actively limiting the duty-cycle variation. In fast varying irradiance environments, it is demonstrated in [41] to reduce the thermal cycling by not tracking very fast irradiance variations, which only slightly increase the harvested energy, but cause damage to the components. If there are no fast variations, the maximum power point is normally tracked by harvesting the maximum energy, as it is commonly done.

D. Thermal Control at System Level

At the next level is the system control, normally suitable in the presence of parallel converters as shown in Fig. 12. The capability of controlling the active power among the parallel converters is shown in Fig. 13 for a difference in the active power distribution of the converters. As it can be seen, the overall losses reduction of the single converter is achieved by loading a converter less than the other one despite the disadvantage of higher losses in the overloaded converter and higher overall losses in the selected operation points. For the proposed case, the losses increase by 1.7 %. Nevertheless, this demonstrates the

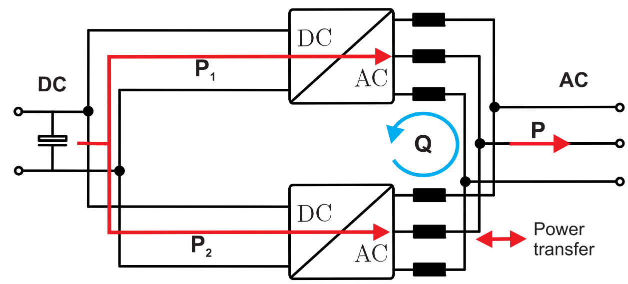


Fig. 12. Active power routing and reactive power routing for low thermal stress.

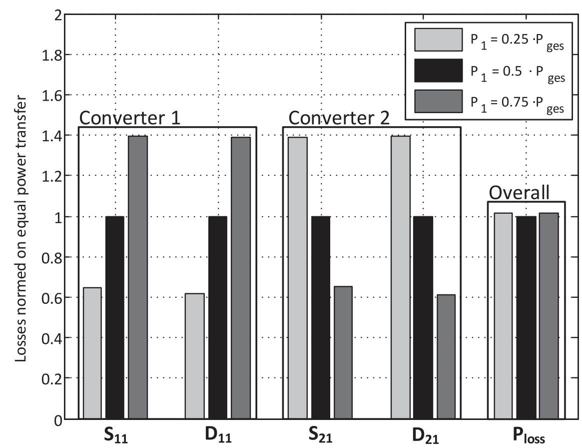


Fig. 13. Loss distribution of the 2L-VSC inverter with different active power loadings.

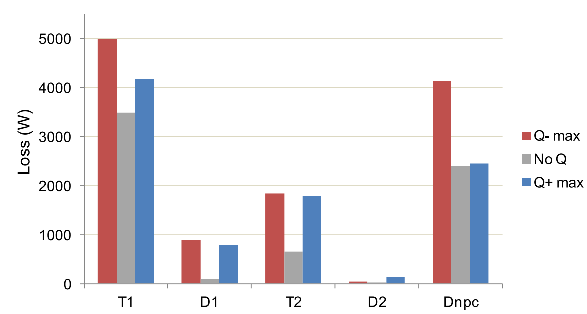


Fig. 14. Loss distribution of the 3L-NPC inverter with different extreme reactive powers (considering parallel converters).

feasibility to control the losses of one of the parallel converters, consequent its junction temperatures.

The reactive power delivered by a converter is a system control reference that is normally not fully utilized, and it is not restricted to the available mechanical/electrical power processed by the converter system, but it can significantly influence the loading of components, and thereby, is suitable to achieve ATC for improved reliability performance of the converter [43]. A simple example can be seen in Fig. 14, where a 3L-NPC converter is operating under maximum overexcited (Q+) as well as underexcited (Q-) reactive power, respectively, with the rated active power output. The influence to the loss distribution of the same 3L-NPC converter by introducing different reactive power can be seen. In addition, the reactive power will not only modify the phase angle between the output voltage and the current of

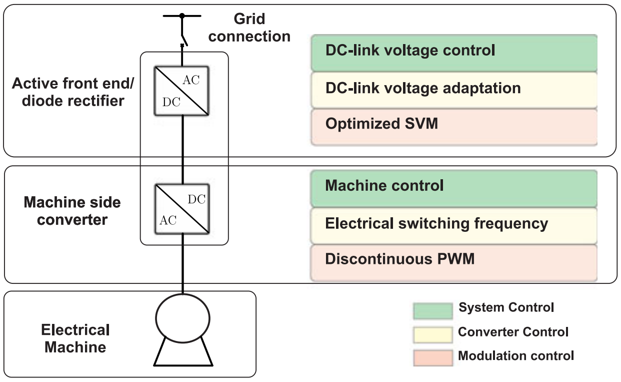


Fig. 15. Drive system and ATC possibilities.

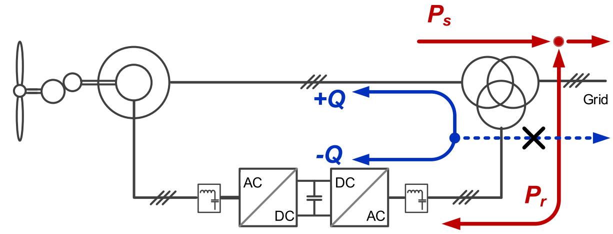


Fig. 16. Compensation scheme of the reactive power in the DFIG wind turbine system.

the converter, but also modify the current amplitude flowing in the power devices, which are all related to the power loss and thermal loading of power devices. This indicates a thermal control case by utilizing reactive power when the 3L-NPC grid-tied inverter is undergoing a power fluctuation. It can be seen that by introducing certain amount of underexcited reactive power to heat up the device during the low-power period, the overall fluctuation of device temperature can be significantly reduced, with slightly increased mean temperature level. According to the lifetime models in Fig. 2, this is a more optimal loading condition with regard to lifetime extension.

V. Application Fields

Active thermal control can be applied to many power electronics areas. There are important differences between the algorithms and the applications. First, the application specific controller algorithms will be examined, and then, they will be categorized for their suitable applications.

A. Electric Drives

Power semiconductors in power converters for electric drives do not only need to be sized to operate reliably for the rated current under the rated machine speed, but also for possible low-speed operation with high torque. During low-speed operation, the electrical fundamental frequency is very low and it results in severe thermal cycling for the power semiconductors, which can quickly lead to a failure. This was first found in [12] and addressed with an algorithm that reduced the switching frequency in order to limit the maximum temperature. Fig. 15 shows the drive system configuration and the thermal control possibilities, where the dc supply for the motor drive is given by a ac/dc rectifier. Usually, the rectifier is constituted of a three-phase diode bridge, so ATC is not normally possible. Some systems present an active front-end, and in this case, the techniques explained in Section IV are possible, especially related to the optimized PWM during LVRT conditions and dc-link voltage adaptation for the control of the switching losses.

Regarding the machine side converter, in [12], [44], and [45], a thermal controller is investigated, which applies the thermal controllers with a junction temperature limitation and an adjustment of the PWM carrier frequency to reduce the losses in the device. This approach is extended in [13] with a fuzzy controller for the detection of power cycling and its reduction. In particular, a filter is employed to detect the magnitude of the thermal cycles, and this information constitutes the feedback signal for two regulators, that dynamically change the switching frequency and the current limit depending on the operating zone (normal, over temperature, power cycling high/low).

Changing the modulation strategy between continuous and 60° DPWM to achieve a loss reduction [18], [46], [47] is another approach. In [25], an ATC of an electric drive composed by an interior permanent-magnet motor and a three-phase, two-level, back-to-back converter is realized by changing the switching frequency and the maximum current limit. Multiple thermal models, for the motor and the power module as well, were implemented and validated with actual measurements. Differently from other solutions presented in the literature, the torque control is realized in a novel way, where the maximum torque per ampere (MTPA) control is substituted with the maximum efficiency per Nm (MEPNm), where the losses of the devices/motor are taken into account in the computation of the optimum current values for the selected output torque. Basically, the MTPA and MEPNm loci differ because the reference for the direct current is optimized for the minimum iron losses.

B. Renewable Energy Generation

In renewable energy generation systems such as wind power or photovoltaic, the converted power is normally weather-based and can impose adverse temperature fluctuations to the power devices, on the other hand, the reliability requirements for these systems are normally high due to high cost of energy [48]. As a result, it is another important and promising application to incorporate various thermal controls methods to achieve more reliable power electronics.

It has been reported in [43] and [49] that the ATC is applied in the wind power generation system by utilizing reactive power to smooth the thermal fluctuation of power device during wind speed variations, either in the double-fed induction generation (DFIG)-based system or full-scale-converter-based system, as shown in Fig. 16. It is noted that in order to amplify the inference on the device temperatures but at the same time also to comply with the grid requirements/codes, the reactive power used for thermal control normally has to be circulated inside the converter system, either between generator and grid-side converter in the DFIG system, or between paralleled converters in the full-scale converter system, as illustrated in Fig. 17. In [50],

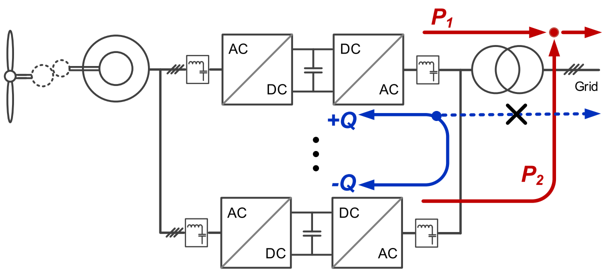


Fig. 17. Reactive power circulating among parallel converters in a wind turbine system.

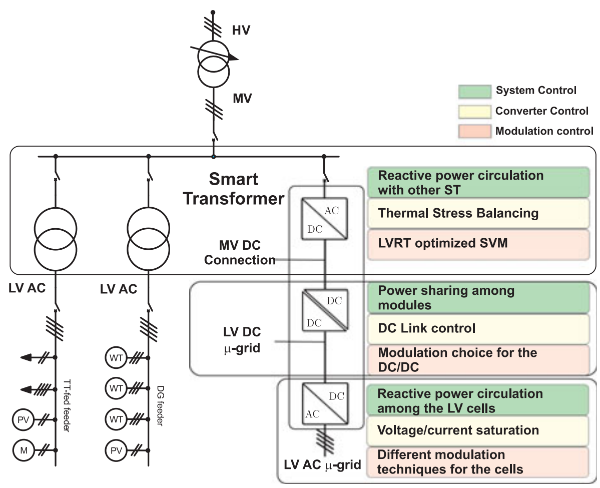


Fig. 18. Smart transformer and ATC possibilities.

a thermal control method controlling the active power of the PV system has been demonstrated. In this method, the maximum power of PV panels is limited to a certain value by a especially modified MPPT control of the PV panels, thereby, the fluctuation of the temperature caused by the randomly variation of solar irradiance/generated power is smoothed, as a result the lifetime of the PV converter is claimed to be extended. However, the drawbacks of reduced energy production and comprised converter efficiency still need to be justified in comparison with the benefits.

C. ST

The ST interfaces the medium- and low-voltage grids, replacing the traditional passive transformer, with the aim of providing additional grid functionalities. From this point of view, a three-stage architecture seems to be the most promising for this application, due to the presence of the dc links, that allow an independent reactive power control in the medium-voltage and low-voltage (LV) side [29]. Fig. 18 shows the ST in an example network and the different control layers with the control objective of each stage. Several of the techniques described in Section IV can be used in the single converter, and will be described in the following. It is important to highlight that the thermal stress is highly mission-profile dependent [51].

At the modulation level, an optimized SVM can be used in the case of NPC converters, in the case of a modular structure like cascaded H-bridge or MMC, the modulation strategy can be used to equalize the thermal stress [27] among different modules, however, the results are very dependent on the number of modules and on the switching frequency. Temperature limitation at the control side can be performed by saturating the control variables of the LV side. As a matter of fact, an ST must provide the active power requested by the LV network, so a way to reduce the loading without affecting normal operation could be to modify the voltage reference in the LV side in order to reduce the power request. Different modulation techniques can be adopted among the LV cells in order to have different thermal stress.

From the point of view of ATC, the system control seems to be the most promising, especially when modularity is considered. Due to high current demand in the LV side, multiple converters will be mandatory, so reactive power circulation [43] can be easily implemented in the modular structure. From the dc/dc side point of view, power can be shared among multiple power converters during partial load conditions, reducing the thermal cycling with respect to an ON/OFF activation system [29]. This idea was expanded to all three stages of the ST [52]–[54], where also a quantification of the stress for a highly fluctuating mission profile was done and it was shown, that the stress for one of the cells was reduced to 23 % of the stress in the balanced case, whereby the stress for the two other cells was six times higher. As a conclusion, the system controls seem to be the most promising techniques to implement ATC in an ST application, since the high voltage and current level demand for a highly modular system. Losses can be modified by circulating the power among the cells or by unbalancing the power sharing to preserve the most damaged cells.

D. Potential of the ATC Approaches for the Different Applications

The potential of the various approaches is highly dependent on the mission profile of the application. For this reason, it is impossible to give a generally valid quantification of the potential.

The basic difference between electric drives and renewable/grid application is the variable speed operation. In fact, in addition to the mission profile variation, the low fundamental frequency operation can already induce very high thermal stress. Instead, for the other two applications, the mission profile is inducing the dominant thermal cycles. The thermal cycles affecting the power semiconductors of renewable energy systems are dependent on the fluctuations induced by the weather conditions. These cycles are expected to occur in more and shorter time periods compared to the power variations of the ST.

As a consequence, for the application in electric drives, the approaches having an immediate effect are promising. This are the gate driver and the switching frequency control in these application. The modulation is a limited instrument also acting on the losses of the single device, which is limited in its application. The control of the dc-link is only feasible if the dc-link is fed by a converter, which is also limiting the applicability of the approach. The mission profile shaping in this application does not seem to be feasible.

TABLE I
POTENTIAL OF THE EXISTENT ATC ALGORITHMS IN THE THREE CONSIDERED APPLICATIONS

ATC Approach	Electric Drives	Renewable Energy Systems	ST
Gate driver T_j control	High	Medium	Medium
Switching frequency control	High	Medium	Medium
Modulation	Medium	Medium	Medium
DC-link voltage control	Medium	Low	Low
Q control	Low	High	Low
P control	No	High	High
Profile shaping	No	High	High

In the application of renewable energy systems, the duration of the power cycles is longer than in the electric drives, which is why the gate-driver-based junction temperature control, the switching frequency control, and the variation of the modulation are counteracted by the costs for the additional losses for potentially long periods. Due to the limitation in the potential dc-link voltage variation, this approach is also not promising. Instead, the control of the active and reactive power in the parallel stacked converters does have a high potential and the shaping of the mission profile is possible as discussed.

For the ST, the promising approaches are similar to the renewable energy systems, because of the very long time periods of the cycles. The mission profile shaping by the saturation of the control variables in the grid instead does not increase costs, but only reduces the stress. This makes it promising to be applied for the shaping of thermal cycles with long time periods. The potential of the existent ATC algorithm is summarized in Table I.

VI. CONCLUSION

The ATC is a technique to reduce the thermal stress of power semiconductors for achieving higher reliability of the system. The active actions can happen at several levels, from the very low level of the gate driver, to the system level, where the presence of multiple power converters is exploited. With the possible benefits of avoiding the components derating or of increasing their lifetime, the thermal limits of the power semiconductors are exploited.

Depending on the application and its mission profile, the severe thermal cycles can have different duration. The controller design needs to consider the redundancies in the system as well as the potential costs for higher losses or less energy production in renewable energy sources. For the three applications of electric drives, renewable energy generation and ST potential ATC algorithms have been reviewed and evaluated. While thermal cycling in short time periods, like it is occurring in electric drives, may justify a short time increase of costs, the compensation of long-term cycles needs to be addressed with other algorithms. For these long-time periods, profile shaping algorithms or algorithms, which utilize potential redundancies seem to be more suitable.

Based on the reviewed material, several techniques showed potential in reducing the thermal stress of the power semiconductors. Linking this stress reduction to an actual lifetime extension is still a missing point, that could be addressed with accelerated tests or with the implementation of pilot projects in cooperation with Industry. This would also allow improved tuning procedures to reach the desired efficiency/lifetime tradeoff.

REFERENCES

[1] J. Lutz, H. Schlangenotto, U. Scheuermann, and R. Doncker, "Semiconductor properties," *Semicond. Power Devices*, pp. 17–75, 2011.

[2] B. Ji, V. Pickert, W. Cao, and B. Zahawi, "In situ diagnostics and prognostics of wire bonding faults in IGBT modules for electric vehicle drives," *IEEE Trans. Power Electron.*, vol. 28, no. 12, pp. 5568–5577, Dec. 2013.

[3] P. S. Chauhan, A. Choubey, Z. Zhong, and M. G. Pecht, *Copper Wire Bonding*. New York, NY, USA: Springer, 2014, pp. 1–9.

[4] I. Kovacevic, U. Drofenik, and J. Kolar, "New physical model for lifetime estimation of power modules," in *Proc. 2010 Int. Power Electron. Conf.*, Jun. 2010, pp. 2106–2114.

[5] M. Ciappa, "Selected failure mechanisms of modern power modules," *Microelectron. Reliab.*, vol. 42, no. 4, pp. 653–667, 2002.

[6] V. Smet *et al.*, "Ageing and failure modes of IGBT modules in high-temperature power cycling," *IEEE Trans. Ind. Electron.*, vol. 58, no. 10, pp. 4931–4941, Oct. 2011.

[7] A. Volke and M. Hornkamp, *IGBT Modules: Technologies, Driver and Application*, 2nd ed. Neubiberg, Germany: Infineon Technologies AG, 2012.

[8] T. Herrmann, M. Feller, J. Lutz, R. Bayerer, and T. Licht, "Power cycling induced failure mechanisms in solder layers," in *Proc. 2007 Eur. Conf. Power Electron. Appl.*, Sep. 2007, pp. 1–7.

[9] M. Schulz, "Thermal management details and their influence on the aging of power semiconductors," in *Proc. 2014 16th Eur. Conf. Power Electron. Appl.*, 2014, pp. 1–6.

[10] H. Huang and P. A. Mawby, "A lifetime estimation technique for voltage source inverters," *IEEE Trans. Power Electron.*, vol. 28, no. 8, pp. 4113–4119, Aug. 2013.

[11] B. Ji, X. Song, E. Sciberras, W. Cao, Y. Hu, and V. Pickert, "Multiobjective design optimization of IGBT power modules considering power cycling and thermal cycling," *IEEE Trans. Power Electron.*, vol. 30, no. 5, pp. 2493–2504, May 2015.

[12] V. Blasko, R. Lukaszewski, and R. Sladky, "On line thermal model and thermal management strategy of a three phase voltage source inverter," in *Proc. 1999 34th Ind. Appl. Conf.*, vol. 2, 1999, pp. 1423–1431.

[13] D. Murdock, J. Torres, J. Connors, and R. Lorenz, "Active thermal control of power electronic modules," *IEEE Trans. Ind. Appl.*, vol. 42, no. 2, pp. 552–558, Mar. 2006.

[14] M. Weckert and J. Roth-Stielow, "Lifetime as a control variable in power electronic systems," in *Proc. 2010 Emobility—Elect. Power Train*, Nov. 2010, pp. 1–6.

[15] S. Yang, A. Bryant, P. Mawby, D. Xiang, L. Ran, and P. Tavner, "An industry-based survey of reliability in power electronic converters," *IEEE Trans. Ind. Appl.*, vol. 47, no. 3, pp. 1441–1451, May 2011.

[16] L. Coffin Jr., "A study of the effects of cyclic thermal stresses on a ductile metal," *Trans. ASME*, vol. 76, pp. 931–950, 1954.

[17] F. Blaabjerg, K. Ma, and D. Zhou, "Power electronics and reliability in renewable energy systems," in *Proc. IEEE Int. Symp. Ind. Electron.*, 2012, pp. 19–30.

[18] A. Wintrich, U. Nicolai, W. Tursky, and T. Reimann, *Semikron, Application Manual Power Semiconductors*. Ilmenau, Germany: ISLE, 2011.

[19] R. Bayerer, T. Herrmann, T. Licht, J. Lutz, and M. Feller, "Model for power cycling lifetime of IGBT modules—Various factors influencing lifetime," in *Proc. 5th Int. Conf. Integr. Power Syst.*, 2008, pp. 1–6.

[20] H. Lu, T. Tilford, and D. Newcombe, "Lifetime prediction for power electronics module substrate mount-down solder interconnect," in *Proc. Int. Symp. High Density Packag. Microsyst. Integr.*, 2007, pp. 1–10.

[21] P. Ghimire, S. Bęczkowski, S. Munk-Nielsen, B. Rannestad, and P. B. Thogersen, "A review on real time physical measurement techniques and their attempt to predict wear-out status of IGBT," in *Proc. 2013 15th Eur. Conf. Power Electron. Appl.*, Sep. 2013, pp. 1–10.

[22] J. Falck, M. Andresen, and M. Liserre, "Active thermal control of IGBT power electronic converters," in *Proc. 2015 41st Annu. Conf. IEEE Ind. Electron. Soc.*, 2015, pp. 000 001–000 006.

[23] Z. Xu, F. Wang, and P. Ning, "Junction temperature measurement of IGBTs using short circuit current," in *Proc. 2012 IEEE Energy Convers. Congr. Expo.*, Sep. 2012, pp. 91–96.

[24] N. Baker, M. Liserre, L. Dupont, and Y. Avenas, "Junction temperature measurements via thermo-sensitive electrical parameters and their application to condition monitoring and active thermal control of power converters," in *Proc. 39th Annu. Conf. IEEE Ind. Electron. Soc.*, Nov. 2013, pp. 942–948.

[25] J. Lemmens, P. Vanassche, and J. Driesen, "Optimal control of traction motor drives under electrothermal constraints," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 2, no. 2, pp. 249–263, Jun. 2014.

[26] M. Andresen, M. Liserre, and G. Buticchi, "Review of active thermal and lifetime control techniques for power electronic modules," in *Proc. 16th Eur. Conf. Power Electron. Appl.*, 2014, pp. 1–10.

[27] F. Hahn, G. Buticchi, and M. Liserre, "Active thermal balancing for modular multilevel converters in HVDC applications," in *Proc. 17th Int. Scientific Conf. Elect. Power Eng.*, 2016, pp. 1–10.

[28] F. Hahn, M. Andresen, G. Buticchi, and M. Liserre, "Thermal analysis and balancing for modular multilevel converters in HVDC applications," *IEEE Trans. Power Electron.*, to be published, doi: 10.1109/TPEL.2017.2691012.

[29] M. Liserre, G. Buticchi, M. Andresen, G. D. Carne, L. F. Costa, and Z. X. Zou, "The smart transformer: Impact on the electric grid and technology challenges," *IEEE Ind. Electron. Mag.*, vol. 10, no. 2, pp. 46–58, Summer 2016.

[30] X. Wang, A. Castellazzi, and P. Zanchetta, "Regulated cooling for reduced thermal cycling of power devices," in *Proc. 2012 7th Int. Power Electron. Motion Control Conf.*, vol. 1, Jun. 2012, pp. 238–244.

[31] P. K. Prasobhu, G. Buticchi, S. Brueske, and M. Liserre, "Gate driver for the active thermal control of a dc/dc GaN-based converter," in *Proc. 2016 IEEE Energy Convers. Congr. Expo.*, 2016, pp. 1–8.

[32] C. Sintamarean, H. Wang, F. Blaabjerg, and F. Iannuzzo, "The impact of gate-driver parameters variation and device degradation in the PV-inverter lifetime," in *Proc. 2014 IEEE Energy Convers. Congr. Expo.*, Sep. 2014, pp. 2257–2264.

[33] L. Wu and A. Castellazzi, "Temperature adaptive driving of power semiconductor devices," in *Proc. 2010 IEEE Int. Symp. Ind. Electron.*, Jul. 2010, pp. 1110–1114.

[34] X. Wang, Z. Zhao, and L. Yuan, "Current sharing of IGBT modules in parallel with thermal imbalance," in *Proc. 2010 IEEE Energy Convers. Congr. Expo.*, Sep. 2010, pp. 2101–2108.

[35] A. Isidori, F. M. Rossi, F. Blaabjerg, and K. Ma, "Thermal loading and reliability of 10-MW multilevel wind power converter at different wind roughness classes," *IEEE Trans. Ind. Appl.*, vol. 50, no. 1, pp. 484–494, Jan. 2014.

[36] H. Wang, R. Zhao, Y. Deng, and X. He, "Novel carrier-based PWM methods for multilevel inverter," in *Proc. 29th Annu. Conf. IEEE Ind. Electron. Soc.*, Nov. 2003, vol. 3, pp. 2777–2782.

[37] T. Bruckner and D. G. Holmes, "Optimal pulse width modulation for three-level inverters," in *Proc. 2003 IEEE 34th Annu. Power Electron. Spec. Conf.*, vol. 1, Jun. 2003, pp. 165–170.

[38] K. Ma and F. Blaabjerg, "Modulation methods for neutral-point-clamped wind power converter achieving loss and thermal redistribution under low-voltage ride-through," *IEEE Trans. Ind. Electron.*, vol. 61, no. 2, pp. 835–845, Feb. 2014.

[39] K. Ma and F. Blaabjerg, "Thermal optimised modulation methods of three-level neutral-point-clamped inverter for 10 MW wind turbines under low-voltage ride through," *IET Power Electron.*, vol. 5, no. 6, pp. 920–927, Jul. 2012.

[40] M. Andresen, G. Buticchi, J. Falck, M. Liserre, and O. Muehlfeld, "Active thermal management for a single-phase H-bridge inverter employing switching frequency control," in *Proc. Int. Exhib. Conf. Power Electron., Intell. Motion, Renew. Energy Energy Manage.*, May 2015, pp. 1–8.

[41] M. Andresen, G. Buticchi, and M. Liserre, "Thermal stress analysis and MPPT optimization of photovoltaic systems," *IEEE Trans. Ind. Electron.*, vol. 63, no. 8, pp. 4889–4898, Aug. 2016.

[42] J. Falck, M. Andresen, and M. Liserre, "Thermal-based finite control set model predictive control for IGBT power electronic converters," in *Proc. 2016 IEEE Energy Convers. Congr. Expo.*, 2016, pp. 1–7.

[43] K. Ma, M. Liserre, and F. Blaabjerg, "Reactive power influence on the thermal cycling of multi-MW wind power inverter," *IEEE Trans. Ind. Appl.*, vol. 49, no. 2, pp. 922–930, Mar. 2013.

[44] L. Wei, J. McGuire, and R. A. Lukaszewski, "Analysis of PWM frequency control to improve the lifetime of PWM inverter," *IEEE Trans. Ind. Appl.*, vol. 47, no. 2, pp. 922–929, Mar. 2011.

[45] J. Lemmens, J. Driesen, and P. Vanassche, "Thermal management in traction applications as a constraint optimal control problem," in *Proc. 2012 IEEE Veh. Power Propulsion Conf.*, Oct. 2012, pp. 36–41.

[46] G. Lo Calzo, A. Lidozzi, L. Solero, F. Crescimbini, and V. Cardi, "Thermal regulation as control reference in electric drives," in *Proc. 2012 15th Int. Power Electron. Motion Control Conf.*, 2012, pp. DS2c.18-1–DS2c.18-7.

[47] M. Weckert and J. Roth-Stielow, "Chances and limits of a thermal control for a three-phase voltage source inverter in traction applications using permanent magnet synchronous or induction machines," in *Proc. 2011 14th Eur. Conf. Power Electron. Appl.*, Aug. 2011, pp. 1–10.

[48] K. Ma, M. Liserre, F. Blaabjerg, and T. Kerekes, "Thermal loading and lifetime estimation for power device considering mission profiles in wind power converter," *IEEE Trans. Power Electron.*, vol. 30, no. 2, pp. 590–602, Feb. 2015.

[49] J. Zhang, H. Wang, X. Cai, S. Igarashi, Y. Li, and Z. Wang, "Thermal control method based on reactive circulating current for anti-condensation of wind power converter under wind speed variations," in *Proc. 2014 Int. Power Electron. Appl. Conf. Expo.*, Nov. 2014, pp. 152–156.

[50] Y. Yang, H. Wang, F. Blaabjerg, and T. Kerekes, "A hybrid power control concept for PV inverters with reduced thermal loading," *IEEE Trans. Power Electron.*, vol. 29, no. 12, pp. 6271–6275, Dec. 2014.

[51] M. Andresen, K. Ma, G. D. Carne, G. Buticchi, F. Blaabjerg, and M. Liserre, "Thermal stress analysis of medium voltage converters for smart transformers," *IEEE Trans. Power Electron.*, vol. 32, no. 6, pp. 4753–4765, Jun. 2017.

[52] M. Liserre, M. Andresen, L. Costa, and G. Buticchi, "Power routing in modular smart transformers: Active thermal control through uneven loading of cells," *IEEE Ind. Electron. Mag.*, vol. 10, no. 3, pp. 43–53, Fall 2016.

[53] Y. Ko, M. Andresen, G. Buticchi, and M. Liserre, "Power routing for cascaded H-bridge converters," *IEEE Trans. Power Electron.* to be published, doi: 10.1109/TPEL.2017.2658182.

[54] G. Buticchi, M. Andresen, M. Wutti, and M. Liserre, "Lifetime based power routing of a quadruple active bridge dc/dc converter," *IEEE Trans. Power Electron.*, to be published, doi: 10.1109/TPEL.2017.2650258.

Markus Andresen (S'15) received the M.Sc. degree in electrical engineering and business administration from Christian-Albrechts-University of Kiel, Kiel, Germany, in 2012. Since 2013, he has been working toward the Ph.D degree under the Chair of Power Electronics at Christian-Albrechts-Unversity of Kiel, Kiel, Germany.

In 2010, he was an intern in the Delta Shanghai Design Center at Delta Electronics (Shanghai) Co., Ltd., China and, in 2017, he was a Visiting Scholar at the University of Wisconsin-Madison, Madison, WI, USA. His current research interests include control of power converters and reliability in power electronics.

Ke Ma (S'09–M'11) received the B.Sc. and M.Sc. degrees in electrical engineering from the Zhejiang University, Hangzhou, China, in 2007 and 2010, respectively, and the Ph.D. degree in Power Electronics from the Aalborg University, Aalborg, Denmark, in 2013.

He was a Postdoc with Aalborg University in 2013 and became an Assistant Professor in 2014. In 2016, he joined the faculty of Shanghai Jiao Tong University, Shanghai, China, as a tenure-track Assistant Professor. His current research interests include the design and enhancement of power electronics reliability in the application of renewable energy and motor drive systems.

Dr. Ma is currently an Associate Editor for the IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, and a Guest Associate Editor for the IEEE JOURNAL OF EMERGING AND SELECTED TOPICS IN POWER ELECTRONICS. In 2016, he was recruited by the "Thousand Talents Plan Program for Young Professionals" of China. He was the receiver of "Excellent Young Wind Doctor Award 2014" by the European Academy of Wind Energy, and a few prized paper awards by the IEEE.

Giampaolo Buticchi (S'10–M'13–SM'17) was born in Parma, Italy, in 1985. He received the master's degree in electronic engineering, in 2009, and the Ph.D. degree in information technologies, in 2013, from the University of Parma, Parma, Italy.

He is currently working as a Postdoctoral Research Associate with the University of Kiel, Kiel, Germany. His research interests include power electronics for renewable energy systems, smart transformer fed microgrids, and reliability in power electronics.

Johannes Falck (S'15) received the M.Sc. degree in electrical and information engineering from Kiel University, Kiel, Germany, in 2015, where he is currently working toward the Ph.D. degree in junction temperature control of power semiconductor devices connected to electric drives to improve lifetime.

His research interests include reliability in power electronics, active thermal control, finite control set model predictive control, induction motor control, model-based junction temperature estimation, and accelerated lifetime tests.

Frede Blaabjerg (S'86–M'88–SM'97–F'03) received the Ph.D. degree in electrical engineering from Aalborg University, Aalborg, Denmark, in 1995.

He was with ABB-Scandia, Randers, Denmark, from 1987 to 1988. He became an Assistant Professor in 1992, an Associate Professor in 1996, and a Full Professor of power electronics and drives in 1998 with Aalborg University. His current research interests include power electronics and its applications such as in wind turbines, photovoltaics systems, reliability, harmonics, and adjustable speed drives.

Prof. Blaabjerg has received 17 IEEE Prize Paper Awards, the IEEE PELS Distinguished Service Award in 2009, the EPE-PEMC Council Award in 2010, the IEEE William E. Newell Power Electronics Award 2014, and the Villum Kann Rasmussen Research Award 2014. He was an Editor-in-Chief of the IEEE TRANSACTIONS ON POWER ELECTRONICS from 2006 to 2012. He is nominated in 2014 and 2015 by Thomson Reuters to be between the most 250 cited researchers in Engineering in the world.

Marco Liserre (S'00–M'02–SM'07–F'13) received the M.Sc. and Ph.D. degrees in electrical engineering from the Bari Polytechnic, in 1998 and 2002, respectively.

He is author of more than 300 technical papers, which received more than 20 000 citations. He is a Full Professor and the Head of the Chair of Power Electronics, University of Kiel, Kiel, Germany. He has published more than 200 technical papers (1/3 in international peer-reviewed journals) and a book at second reprint and also translated in Chinese. These works have received more than 15 000 citations, for this reason he is listed in ISI Thomson report "The world's most influential scientific minds" from 2014.

Prof. Liserre has received the European ERC Consolidator Grant, one of the most prestigious in Europe. He is member of the IEEE Industrial Applications Society, IEEE Power Electronics Society, IEEE Power & Energy Society, and IEEE Industrial Electronics Society (IES). He did serve all these societies in various capacities such as a Reviewer, an Associate Editor, an Editor, a Conference Chairman, or a Track Chairman. He has been a Founding Editor-in-Chief of the IEEE INDUSTRIAL ELECTRONICS MAGAZINE, a Founding Chairman of the Technical Committee on Renewable Energy Systems, and IES Vice-President responsible of the publications. He has received several IEEE Awards.